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AN EXPERIMENTAL AUTOMATIC WIDE RANGE INSTRUMENT TO MONITOR THE ELECTROSTATIC FIELD AT THE SURFACE OF AN AIRCRAFT IN FLIGHT

by

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MINISTRY OF TECHNOLOGY
FARNBOROUGH HANTS

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SUMMARY

A device has been constructed to monitor automatically the magnitude and polarity of electrostatic fields associated with an aircraft in flight. It is small, self-contained apart from an ancillary photographic recorder, and operates from the aircraft 400 Hz supply. Logarithmic amplifier techniques are used to accommodate the large signal range of 400 V/m to 300 kV/m.

Departmental Reference: Avionics 19

CONTENTS

1 INTRODUCTION

Investigations into the accumulation of static charge on helicopters have revealed the need for a means of continuously monitoring the electrostatic fields associated with an aircraft in flight. It was decided that for this purpose an instrument of the type classified by Chalmers[1] as a field mill was the most suitable. Such a device was used in a programme of work previously reported[2,3]. This early mill and its associated equipment, illustrated in Figs.1 and 2, suffered from two principal disadvantages. An observer was needed to operate the recording equipment and reset the measurement range as field conditions altered. Secondly, the electronic circuits were housed in somewhat cumbersome units external to the mill itself. It was therefore decided to construct a completely automatic field mill which would be self-contained apart from an ancillary recorder and optional indicating instruments.

This Report describes an instrument designed to fulfil the above requirements. It is capable of continuously monitoring field strengths of either polarity in the range 400 V/m to 300 kV/m, with an accuracy better than 10% for fields greater than 2 kV/m. Use is made of a logarithmic scale in preference to range changing techniques to accommodate the wide signal range. This simpler system is permissible in view of the absence of any high accuracy requirements; since the prime use of the equipment on aircraft will be to correlate such phenomena as the onset of radio interference and windscreen discharging with the degree of static activity, rather than to make absolute measurements of field strength. The field magnitude and polarity information may either be recorded or displayed in real time. The response of the system is adequate to follow most naturally occurring field changes, exceptions being the rapid changes associated with lightning strikes. The instrument will operate in ambient temperatures between -16°C and +50°C, and can be powered from an aircraft three phase 400 Hz supply. Either 115 V or 200 V is acceptable without internal rewiring.

2 THEORY OF THE FIELD MILL

Fig.3a-e illustrates the charge movements which occur during the operation of the field mill. In these diagrams a collector plate is connected to the frame (earth) by a resistance. Above the collector a screening plate, also connected to the frame, is shown moving from left to right. As the collector plate becomes screened from the field, charge which was previously residing on the top surface (Fig.3a) can no longer link with the opposite charge inducing

it and must therefore flow down to the frame through the resistance (Fig.3b), until the collector is completely screened and no charge remains on it (Fig.3c). As the screening plate continues to move to the right, bound charge must again exist on the top surface of the collector and therefore flows up from the frame to give that condition (Fig.3d). Finally the cycle is complete when the screening plate is just clear of the collector (Fig.3e). It follows that if a succession of screening plates were made to pass over the collector an alternating voltage waveform would be developed across the resistance, the amplitude of which would be proportional to the surface charge density and hence to the field strength.

Fig.4 shows the arrangement used in the present mill. The collector plate and screening rotor are each of Maltese Cross shape and produce four complete cycles of output for each revolution. From the current flow directions indicated in Fig.3 it will be seen that field polarity reversal produces 180° phase shift in the output signal. This allows polarity to be determined by comparing the phase of the output signal with that of a reference generator on the rotor shaft.

An expression for the output voltage may be obtained by regarding the mill as a generator passing current through the impedance formed by the resistance connected between collector and frame in parallel with the collector to frame capacitance. If small changes in collector-frame capacitance due to the rotation of the rotor are ignored, Mapleson and Whitlock have shown[4] that for a triangular collector exposure waveform the peak output voltage V is given by

$$V = \frac{\varepsilon \; E \, A \, \omega \, R \, (1 - \exp(-\pi/\omega \, C \, R))}{\pi(1 + \exp(-\pi/\omega \, C \, R))} \qquad (1)$$

where R = the resistance connected between collector and frame

C = collector-frame capacitance

A = maximum area exposed

E = incident field strength

ε = permittivity

ω = angular frequency of the signal generated.

If $\omega^2 C^2 R^2 \gg 1$ equation (1) finally simplifies to

$$V = \varepsilon \; E \, A/2C \qquad (2)$$

and the output is independent of R and ω. Clearly to achieve this, either ω, C or R can be made very large. However the magnitude of ω is limited by the rotor shaft speed allowable for reasonable earthing brush life and the number of collector plate segments that can be used (Fig.4), whilst increasing C decreases the sensitivity and is therefore not desirable. Very high value resistors are available but their usefulness is limited by the shunting effect of the collector-frame leakage resistance. This resistance will vary with humidity, surface contamination, etc. For example a suitable value of resistance required to make $\omega^2 C^2 R^2 \gg 1$ would be about 100 MΩ for the present mill which has a collector-frame capacitance of 45 pF and an angular frequency of 500 π radians per second. Thus the effect of surface leakage cannot be neglected.

This difficulty is overcome in the present mill by feeding the output from the collector plates into a virtual earth amplifier* as shown in Fig.5. The output voltage developed across the feedback impedance Z_f is very nearly $-i\ Z_f$ and the values of C and R in equation (1) must be replaced by the capacitive and resistive components of Z_f (C_f and R_f) which can be closely controlled. If this feedback impedance is made a capacitance the resistive component is then its very high leakage resistance and $\omega^2 C_f^2 R_f^2$ can be made $\gg 1$. Thus the conditions for equation (2) are satisfied, wherein the output voltage is independent of resistive and frequency terms and hence to variations in them. In addition it will be noted that the output voltage is now also independent of variations in collector-frame capacitance.

With capacitive feedback the output waveform is similar to the collector area exposure waveform, as the current generated by the mill is the rate of charge movement and $v_C \propto \frac{1}{C} \int i\ dt$. It may be noted that Ref.4 shows equation (2) also holds for a sinusoidal exposure waveform, again provided $\omega^2 C^2 R^2 \gg 1$. Consequently the observed waveform (Fig.18) which is intermediate between sinusoidal and triangular, would be expected to follow a law very similar to that of equation (2). The distortion arises because of field fringing effects between rotor and collector.

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* The negative current feedback through Z_f (Fig.5) is constrained to be nearly equal in magnitude to the input current i. Consequently little current flows to earth through R and C and the amplifier input remains virtually at earth potential.

3 DESCRIPTION OF THE INSTRUMENT

Fig.6 shows a block diagram of the complete system. The virtual earth input stage converts the alternating current generated by the mill to a voltage signal which is rectified by the peak voltage detector. This provides a positive voltage level to drive the logarithmic amplifier whose output will generally be fed to a recorder, but if required can be displayed on a meter. A simple form of temperature compensation is incorporated in the logarithmic amplifier stage to counteract its inherent variation in gain with operating temperature (see section 4.3). Polarity information is derived from a signal provided by the peak detector stage and is normally recorded as a second trace. Integrated circuit amplifiers are used where possible because of their small size, reliability and convenience in circuit design.

The construction of the mill may be seen from the photographs shown in Figs.7 and 8. The rotor is driven by a three phase motor running at 12000 rev/min geared down in the ratio 3.2:1 giving a driving torque at the mill shaft of about 150 g cm and a signal frequency of 250 Hz. Two sets of silver graphite brushes running on rhodium plated tracks are used to ensure adequate earthing of the rotor to the frame. The reference generator is mounted on the mill shaft and is shown diagrammatically in Fig.4. The stator of this generator may be turned in its housing to adjust the phase of the reference signal relative to the field signal.

The power supplies required are 400 Hz three phase at either 200 V or 115 V and approximately 20 VA. The voltage selection is made by changing the external connections to one of the six way Mk.VI connectors at the back of the instrument. Other connections brought out are for the recorder and indicator circuits (Mk.VI) plus an output from the virtual earth amplifier included primarily for convenience during testing.

The field mill is designed to project through the aircraft skin, preferably in a downward facing attitude to avoid the ingress of rain. A cover attached by a bayonet fastening is provided for protection and calibration purposes when the aircraft is on the ground. It must be removed when the instrument is in use. The design of this cover is such as to provide an outer earthed screen with an isolated inner plate parallel to and spaced approximately 1 cm away from the mill collector plate. Voltage connection to the inner plate is afforded by the central terminal shown in Fig.9. Also shown in Fig.9 is a SFIM photographic recorder Type A203H suitable for use in flight. The mill without the cover weighs 3 lb 6 oz (1.53 kg) and the recorder 4 lb 12 oz (2.15 kg).

The field signal available to drive the recorder ranges from approximately +3.5 V (minimum field) to -3.5 V (maximum field), whilst the polarity signal is approximately 2 to 8 μA over the field range measured, reversing direction with field polarity.

4 CIRCUIT DETAILS

4.1 The virtual earth amplifier

The detailed circuit is shown in Fig.10. A gain of about 30 within the feedback loop is found to give satisfactory independence from the collector-frame resistance and capacitance values. A μA702C integrated circuit stage connected as a phase inverter is preceded by a source follower connected field effect transistor to obtain the necessary phase inversion with high input impedance.

The value of the overall feedback capacitor selected (220 pF) is such that at the minimum field gradient (400 V/m) an output swing of approximately 8 mV peak to peak is produced, with a corresponding swing of about 6 V at maximum field (300 kV/m). As the operating frequency is low (250 Hz), the stabilization of the μA702C stage is achieved by a capacitance to earth from pin 6 and a 100 Ω resistance at the output, as suggested in Ref.5.

It was shown experimentally that the resistance from the collector plate to earth (nominally 1 MΩ) must be reduced to 20 kΩ to halve the amplitude of the output from this stage. This is a measure of the effectiveness of the virtual earth amplifier and is considered to be more than adequate protection against the effects of rain and condensation on the insulation resistance of the mill.

4.2 The peak voltage detector

The peak voltage detector stage shown in Fig.11 follows very closely that given in section 3.2.8 of the circuit application notes[5] for the integrated circuit amplifier used. It serves the dual purpose of providing a positive voltage to drive the logarithmic amplifier and an alternating signal for the polarity sensing circuits. In this circuit feedback occurs when one of the two diodes (D_2, D_3) is biased into conduction, that is when the output of the μA702C is more than ±0.3 to 0.7 V (a temperature dependent figure). As the minimum open loop gain of the amplifier is quoted as 1500, the diodes will certainly conduct well for inputs in excess of 1 mV peak and satisfactory peak detection of the minimum input signal (4 mV peak) is obtained.

The logarithmic amplifier drive signal is developed across the 47 µF output capacitor and is very nearly equal to the peak of the negative half cycle of the field signal. Consider the case when the capacitance is initially uncharged and an alternating voltage is applied starting at about 1 mV below zero and going negative on the first half cycle. The µA702C output voltage will increase positively charging the capacitor via diode D_3, so that its voltage is substantially equal but of opposite polarity to the input. This continues until the negative peak value is reached. Diode D_2 remains biased off during this period. It will be noted that the gain of the circuit is set to very nearly unity by the equal value input and feedback resistors. The discharge time constant of the capacitor into the logarithmic amplifier is such that the peak voltage is almost maintained until a slight replenishment occurs at the next negative peak. The charge and discharge time constants of this capacitor also decide the response of the system to changing fi l gradients and are such that, with the exception of lightning strokes, all normally occurring rates of change can be followed.

Diode D_2 and the associated 10 kΩ resistance prevent hard negative saturation at the output of the amplifier on positive half cycles.

The input signal to the phase sensitive rectifier is taken from output B (Fig.11). As the 47 µF capacitor is maintained at a positive voltage nearly equal to the peak voltage of the alternating input signal and this is fed back to the input of the amplifier the total input signal at pin 2 of the µA702C is positive for most of each cycle. Consequently the output voltage is then negative and feedback occurs through diode D_2. However, during that part of the cycle when the capacitor is receiving charge the output must be positive. Thus the output swing will always of necessity be at least sufficient to bias diodes D_2 and D_3 into conduction in turn. That is to say, the minimum peak to peak voltage swing on the output will be equal to twice the voltage needed to bias a diode into conduction, say 0.6 V total. The maximum input swing is limited to approximately 5 V peak to peak, so that although an input level variation of 750:1 is handled, the signal transmitted to the input of the phase sensitive rectifier varies only in the ratio of some 10:1.

4.3 The logarithmic amplifier stage

This follows the general lines of a logarithmic amplifier previously described[5] the main changes being, the use of a more readily available dual transistor, and of a different type of integrated amplifier to obtain conformity

with those in the rest of the equipment. Referring to Fig.12, the first μA702C is a phase reversing operational amplifier having an input resistance of 2.2 kΩ and using one half of the dual transistor CV 7479 as the feedback element. The emitter base voltage developed across this part of the transistor is offset by that across the other half connected as a diode. This enables almost the full range of output swing of a second μA702C, connected as a non phase inverting high input impedance amplifier, to be used.

Ref.5 contains a brief discussion indicating that a linear relationship between output voltage and the natural logarithm of the input voltage may be expected over a very wide signal range, and that the gain of the circuit will be subject to a thermal sensitivity of about 0.3%/°C. The discussion is based on the fact that the collector current and base-emitter voltage of a transistor are related by the expression

$$I_C \propto \exp\left[\frac{q\ V_{BE}}{kT}\right] \tag{3}$$

where q is the charge of an electron, V_{BE} is base-emitter voltage, k is Boltzmann's constant and T is the absolute temperature.

This expression assumes V_{CB} (the voltage between collector and base of the transistor) to be zero. The relationship has been experimentally verified over a range of some nine decades of current for a well made silicon transistor. It is in error at very low currents due to collector leakage and at high currents because of base spreading resistance effects.

When a transistor is used as the feedback element in an operational amplifier circuit, the requirement that V_{CB} shall tend to zero necessitates the use of an amplifier with an extremely high gain for operation over a range of inputs approaching the theoretical limit of nine decades. However only three decades are needed in the equipment under discussion and the μA702C possesses adequate gain for this purpose. The leakage current of the feedback transistor, part of CV 7479 (2N 2060), is quoted at a maximum of 2×10^{-3} μA with a V_{CB} of 80 V at 25°C. Since V_{CB} will never exceed a few millivolts in this circuit the leakage current will always be very much smaller than the input current to the logarithmic amplifier, which ranges from about 2 μA to 1.5 mA.

A substitution of values in the exponential expression (equation (3)) shows that a decade of input signal produces a voltage change of very nearly 60 mV in V_{BE}, i.e. at the output of the first integrated amplifier. As the output voltage is always negative, the output moves from near zero to a more

negative value as the signal level increases. This is inconvenient, because in order to use the full output swing of the second μA702C an input to it which moves symmetrically about zero level is necessary. The second part of CV 7479 is therefore connected as a diode and fed with a constant biasing current. If the current flowing in the two transistors of CV 7479 are equal, the V_{BE} values are (ideally) equal and the input voltage to the second μA702C stage is zero. Adjustment of the bias current allows the mid-point of the logarithmic amplifier output swing to be preset to a chosen field gradient. The gain of the second stage is set by the ratio of the feedback resistance to pin 2 of the μA702C (15 kΩ plus some temperature compensating resistance) and the 470 Ω resistance to earth. The output swing is from approximately 3.5 V corresponding to a field of 400 V/m, to approximately -3.5 V corresponding to 300 kV/m. The overall sensitivity is about 2.4 V per decade of input signal. In order to obtain a conventional display when the output is shown on a centre zero voltmeter, the connections to the meter are interchanged so that increasing field deflects the needle to the right, and this convention has been followed in Figs.15-17.

Transistor CV 7479 contains the feedback transistor and the diode connected transistor in the same package, so that both are at essentially the same temperature and any differential thermal effects on their V_{BE} values tend to cancel. However equation (2) above shows that the voltage gain of the first stage of the logarithmic amplifier varies with the absolute temperature, having in fact a coefficient of approximately 0.3%/°C at normal laboratory temperature. A temperature sensitive resistance (Brimistor) is therefore connected in the feedback circuit of the second μA702C to compensate for this temperature coefficient. Fig.17 shows that this compensation is satisfactory.

A temperature dependent voltage drift can appear at the input to the logarithmic amplifier, and this causes a departure from linearity in the logarithmic response at low values of the field gradient. It arises because the μA702C integrated circuits used in the peak detector and the first stage of the logarithmic amplifier each have small bias and offset input currents which vary with temperature and between individual units. Particularly under low ambient temperature conditions these effects may approach or exceed the useful signal produced by a weak field. Such a condition arises in Fig.17a, where the outputs for both positive and negative fields of less than 300 V/m are limited to -3.8 V. It is therefore desirable to choose the μA702C elements for the peak

voltage detector and the logarithmic amplifier so that bias and offset currents match as nearly as possible.

The circuit is set up at laboratory temperature by adjusting the potentiometer at the input to the logarithmic amplifier to give a linear output to as low a field as possible. This test is then repeated at different temperatures and the 2.2 kΩ resistance, starred in Fig.12, trimmed to minimise the effect of temperature. In general the potentiometer wiper will not be set in a central position and the response at low signal levels is therefore slightly affected by changes in negative rail voltage.

4.4 The polarity sensing circuits

The polarity sensing circuit is shown at Fig.13. As mentioned earlier this provides phase sensitive rectification of a field signal from the peak detector. Transistors CV 7112 are alternately switched into the conducting state by the waveform applied to their bases from the reference generator. This waveform, at the same frequency as the field signal, is synchronised to it by rotating the generator stator in its housing until the polarity output shows a maximum amplitude. Thus the two waveforms are in phase for one field polarity and in antiphase for the other. The input from the peak detector is consequently full wave phase sensitively rectified by the transistors. The output is either displayed on a centre zero meter or fed directly to a suitable recorder.

Although the field signal varies in amplitude in the ratio of 750:1 over the range of fields monitored, the polarity signal only alters in the ratio of approximately 4:1, being limited by the action of the peak detector (as explained in section 4.2) and further limited by the diodes CV 7040 shown in Fig.13.

4.5 Power supply circuits

The power supplies required for the amplifiers are 12 V and -6 V at approximately 20 mA. As shown in Fig.14 these voltages are obtained from a full wave bridge and zener diode circuit, fed from an isolating transformer. This transformer is connected via a capacitor across one winding of the mill drive motor. The capacitor is used to drop the input voltage so that a physically smaller transformer may be used. The motor is so wound that it can be run from a 115 V supply in delta connection or from a 200 V supply in star connection. By suitably arranging the connections to the input plug the complete system can be run from either voltage.

5 PERFORMANCE

Figs.15, 16 and 17a-c are calibration curves for the first field mill made to the present design. Fig.15 shows the curves produced when the mill is placed in a calibration rig specially designed to give a uniform field. It consisted of a pair of 2 ft (61 cm) square potential plates placed 10 cm apart. It will be seen from Fig.15 that the calibration is substantially linear but that positive and negative fields differing by some 15% produce the same output. This is due to the asymmetrical waveform generated by the mill (Fig.18), caused by fringing effects between the rotor and collector. Since the peak detector circuit uses only the negative peak of the mill output irrespective of the field polarity, the above mentioned change of sensitivity with polarity occurs.

Fig.16 shows a plot of mill output versus voltage applied to the calibration cover and comparison with Fig.15 demonstrates that 11 V applied to the cover produce an equivalent field of 1 kV/m and that this proportion holds at least up to fields of 100 kV/m. Fig.17a-c shows the effect of ambient temperature on the mill calibration. These curves were obtained using the calibration cover, because of the limited size of the temperature chamber.

The non-linearity shown in the figures at fields less than about 2 kV/m may be due to several causes, for example: contact potential between the different parts of the mill creating an error field; 'noise' pick up; differential offset voltages at the input of the logarithmic amplifier; and current leakage from the FET causing a small polarising voltage at the collector. It is felt that the most serious effect is noise pick up. The differential offset voltage causes a departure from linearity in the same direction for both field polarities and is explained in section 4.3. This effect becomes important at about -16°C (Fig.16a) and is even more serious at lower temperatures. It is to a large extent associated with the limited temperature range of the μA702C (0° to +70°C) which were readily available when the circuits were constructed. It is therefore surprising that the equipment worked satisfactory at -16°C and even down to -40°C with limited sensitivity.

The slight curvature shown in Figs.15 and 16 at fields above 200 kV/m is thought to be caused by corona effects from the sharp corners of the mill rotor, collector and mounting collar. This would be expected to differ slightly between the two methods of calibration and would eventually set an upper limit to the field strength that can be measured.

It can be shown that if the curves of Fig.16 are taken as references and allowance is made for the differing sensitivity to positive and negative fields, the mill gives results accurate to 10% for fields in excess of 2 kV/m, over the temperature range -16°C to +50°C. The absolute accuracy becomes poor for fields much below 1 kV/m but the mill will nevertheless operate down to about 400 V/m.

Fig.19 shows a record made for calibration purposes. This shows the response to sudden reversals in field. The changeover time of the switch used to reverse the potential to the calibration cover can be seen on the traces and is from the point where the positive field starts to decay on the natural discharge time of the cover, to where the field abruptly changed from positive to negative as the switch closes to the negative potential. This response is clearly adequate for all but the most rapid field gradient changes.

6 CONCLUSIONS

6.1 An experimental field mill has been constructed which will monitor automatically both positive and negative field strengths in the range 400 V/m to 300 kV/m in ambient temperatures between -16°C and +50°C.

6.2 The equipment is relatively small and compact and needs only a suitable recorder to form an airborne field measurement system which does not require an observer.

6.3 The accuracy below about 2 kV/m is somewhat dependent on the noise environment in which the instrument is operating but above that value is better than ±10%, provided separate calibration curves are used for positive and negative fields.

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No.	Author	Title, etc.
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5	The applications engineering staff of the SGS-Fairchild Group	The application of linear microcircuits. Aylesbury, Buckinghamshire, SGS-Fairchild Ltd. (1968)

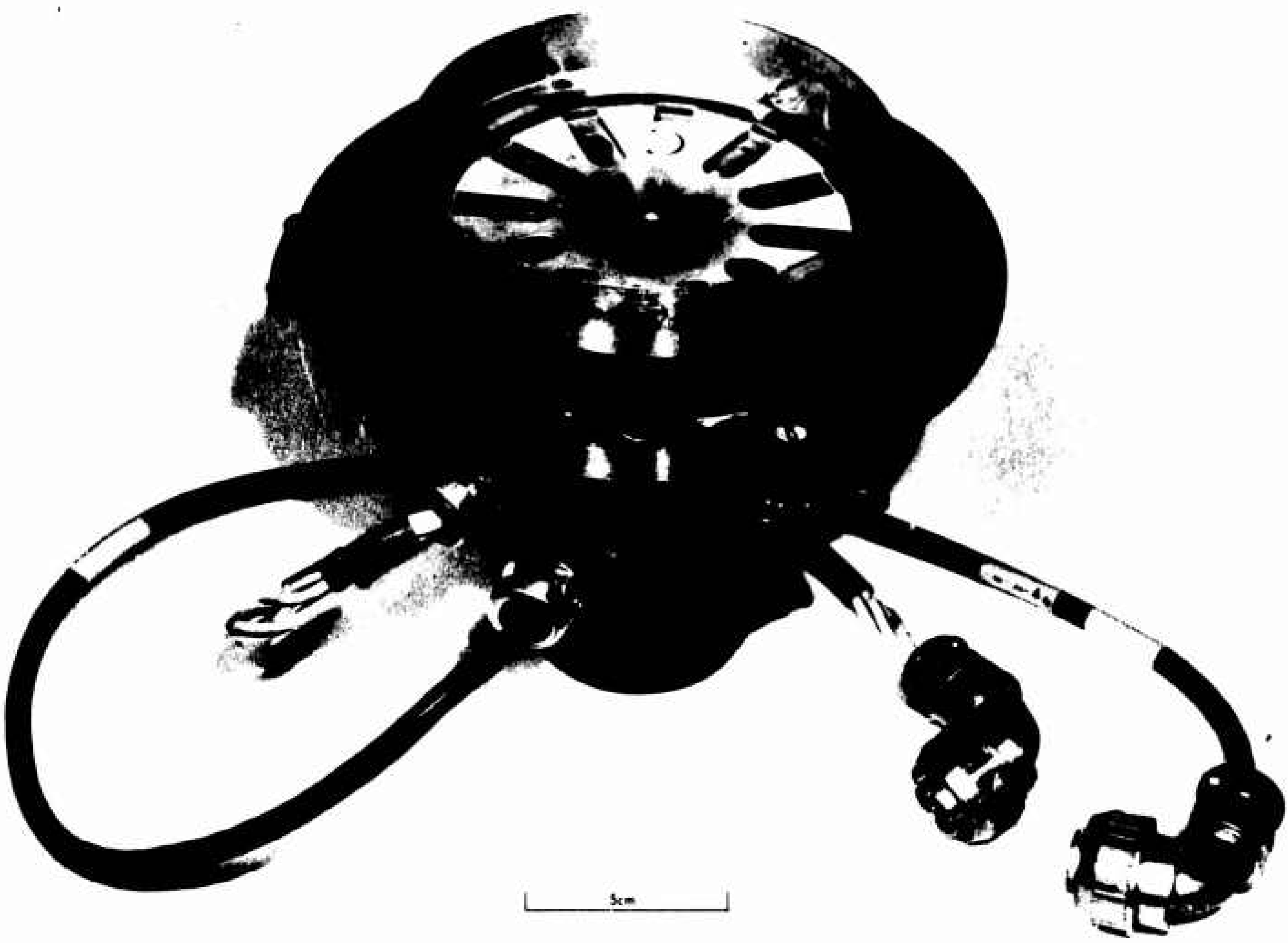

Fig.1. Earlier field mill developed for investigation of static build up on helicopters

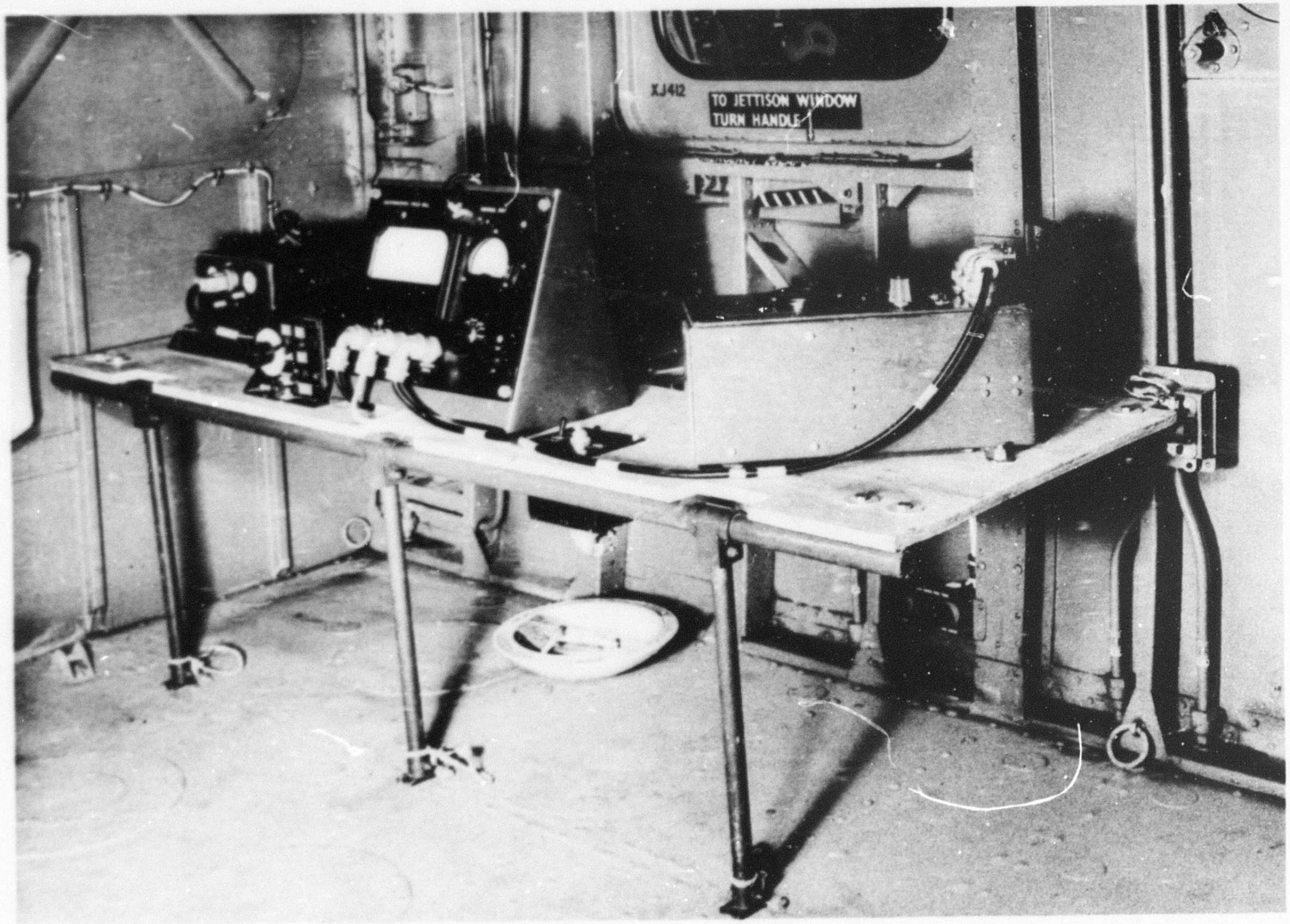

Fig.2. Ancillary equipment for use with the field-mill shown in Fig.1, including power supply, main amplifier and visual display unit, and galvanometer recorder

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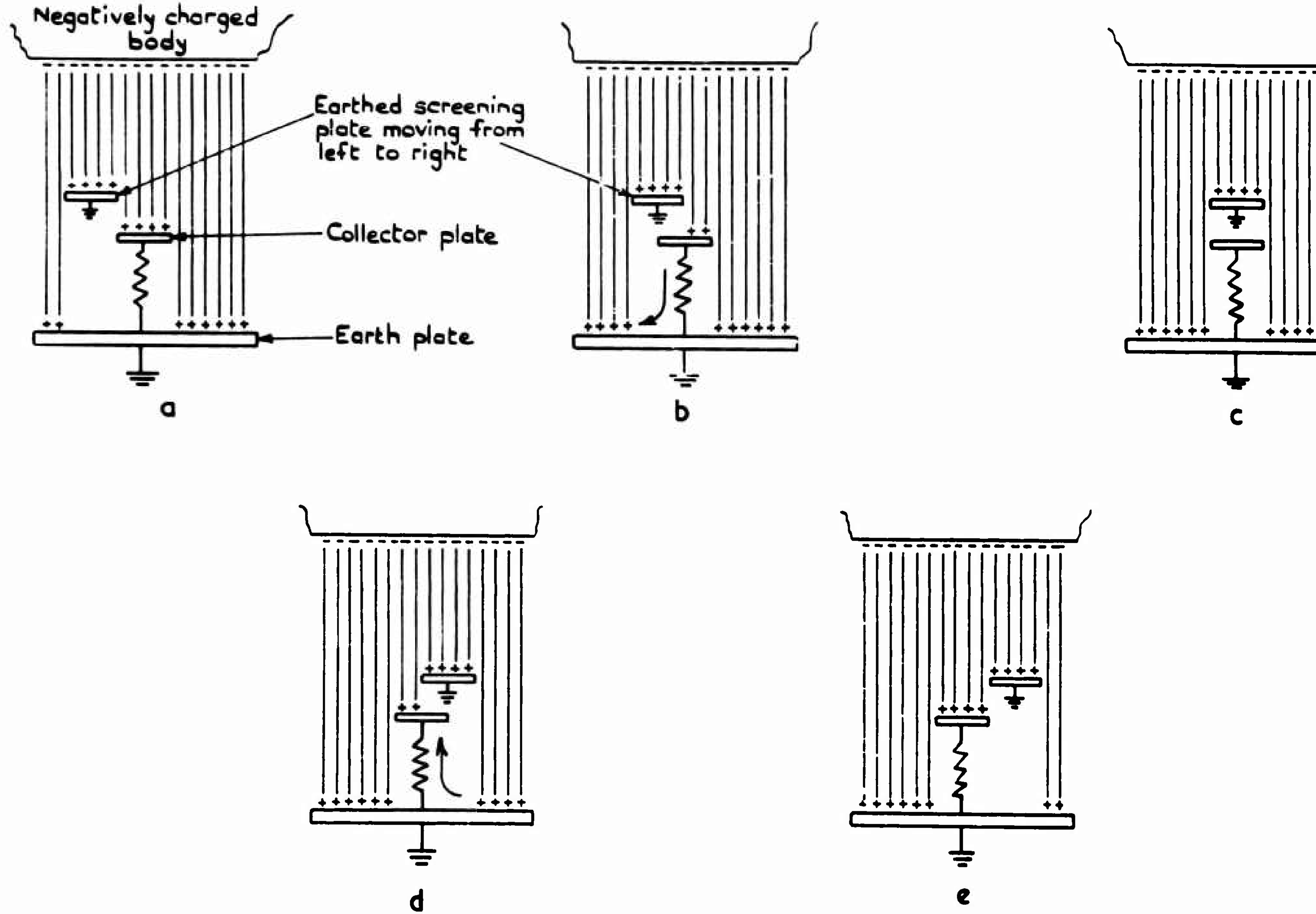


Fig. 3 a-e Operation of field mill

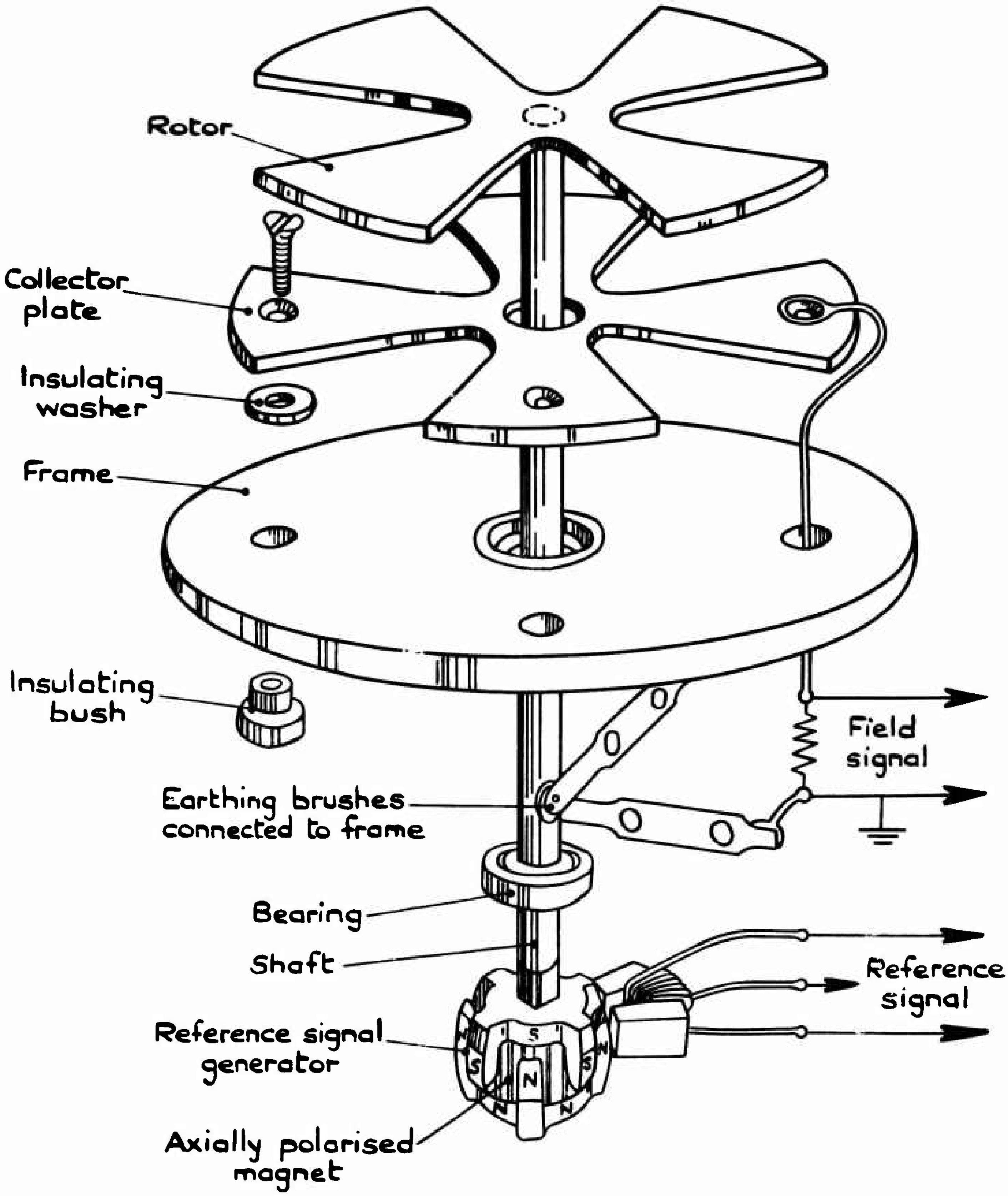
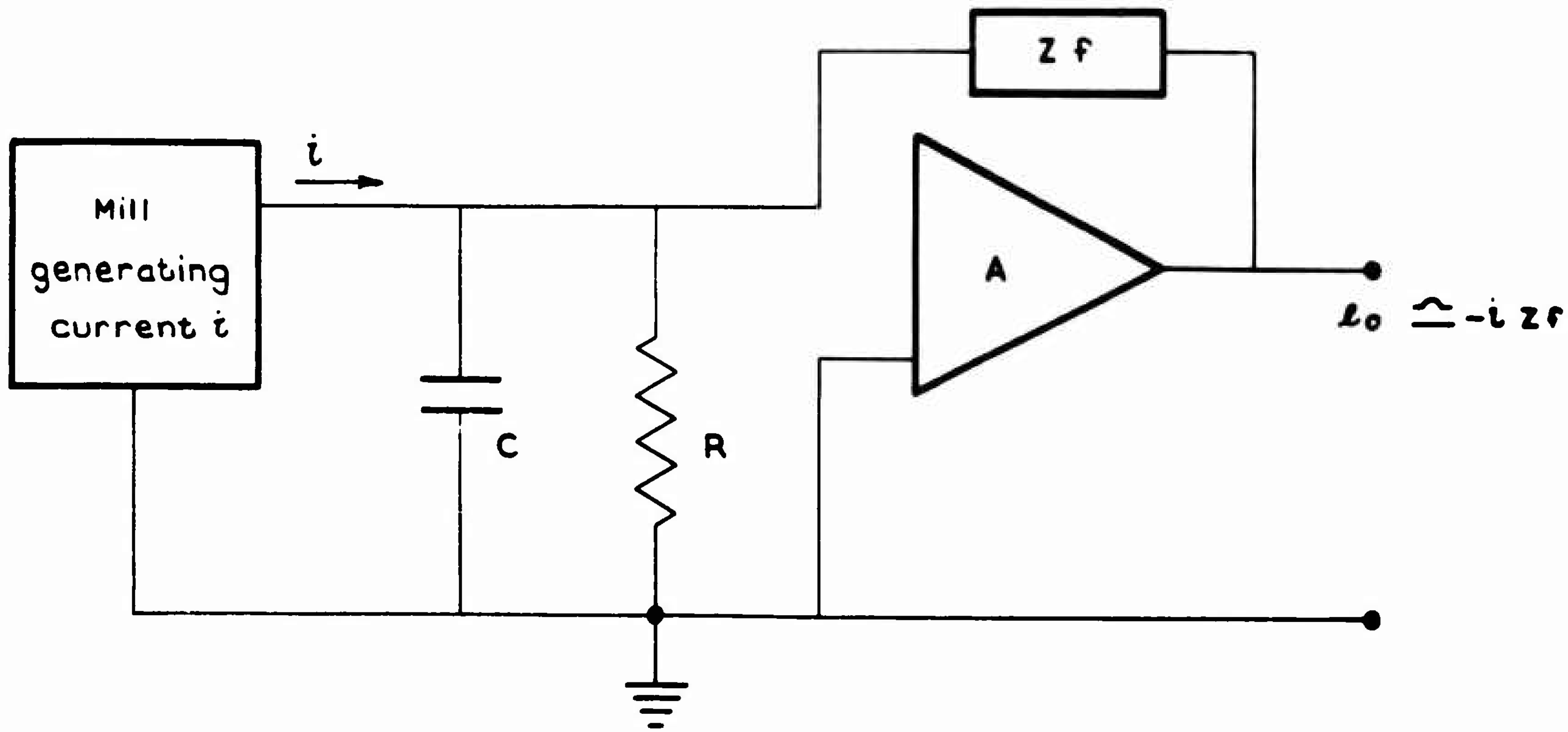


Fig.4 The essential parts of the new field mill



C — Mill capacitance plus all strays including Δc
R — Total resistance from collector to frame including leakage
A — High gain phase reversing amplifier

Fig. 5 The field mill connected to a virtual earth amplifier

Fig. 6

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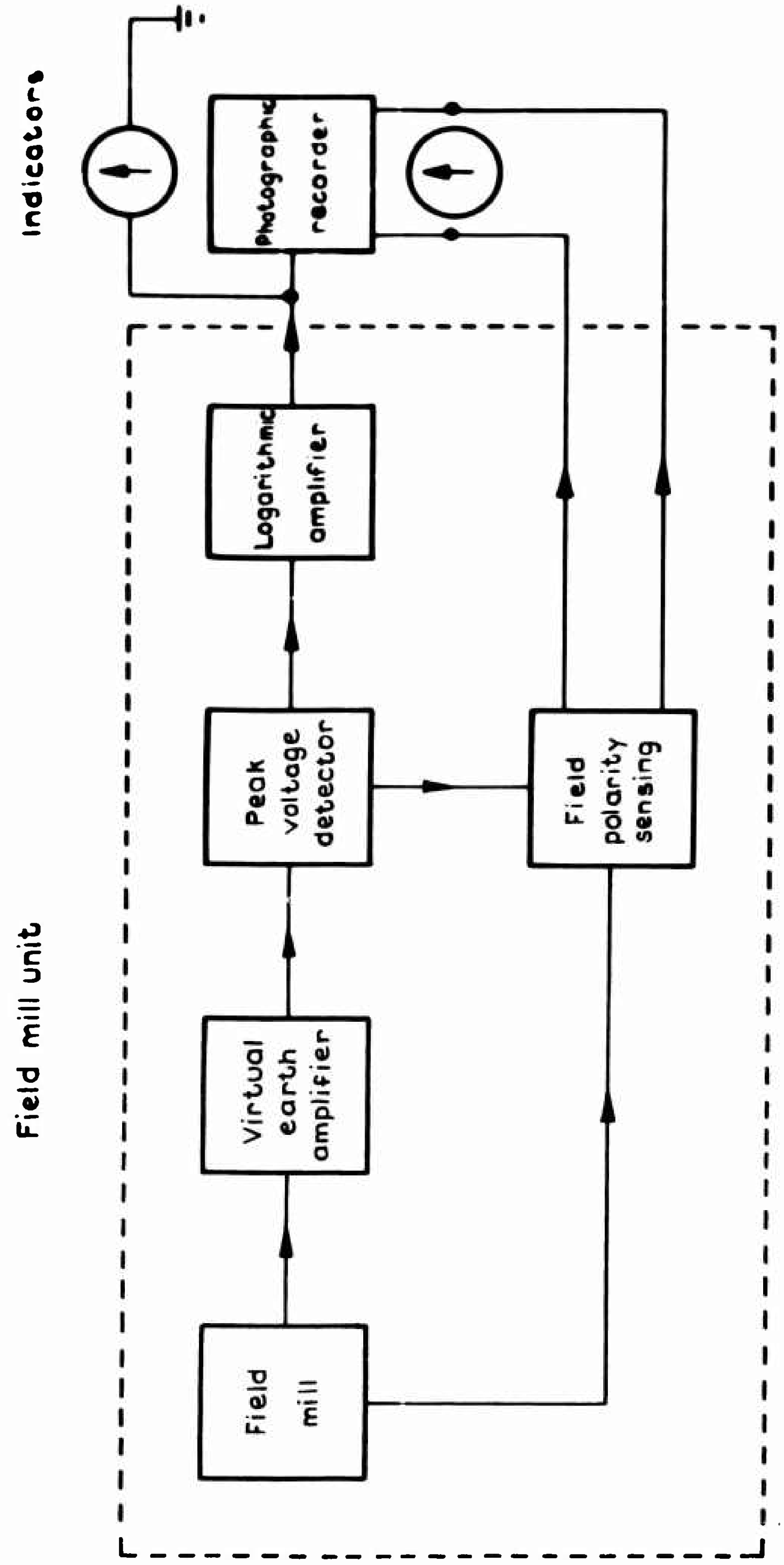

Fig.6 Block diagram of the complete system

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·08 ·14 ·3 42 ·52 ·68 1·2 1·6 1·8

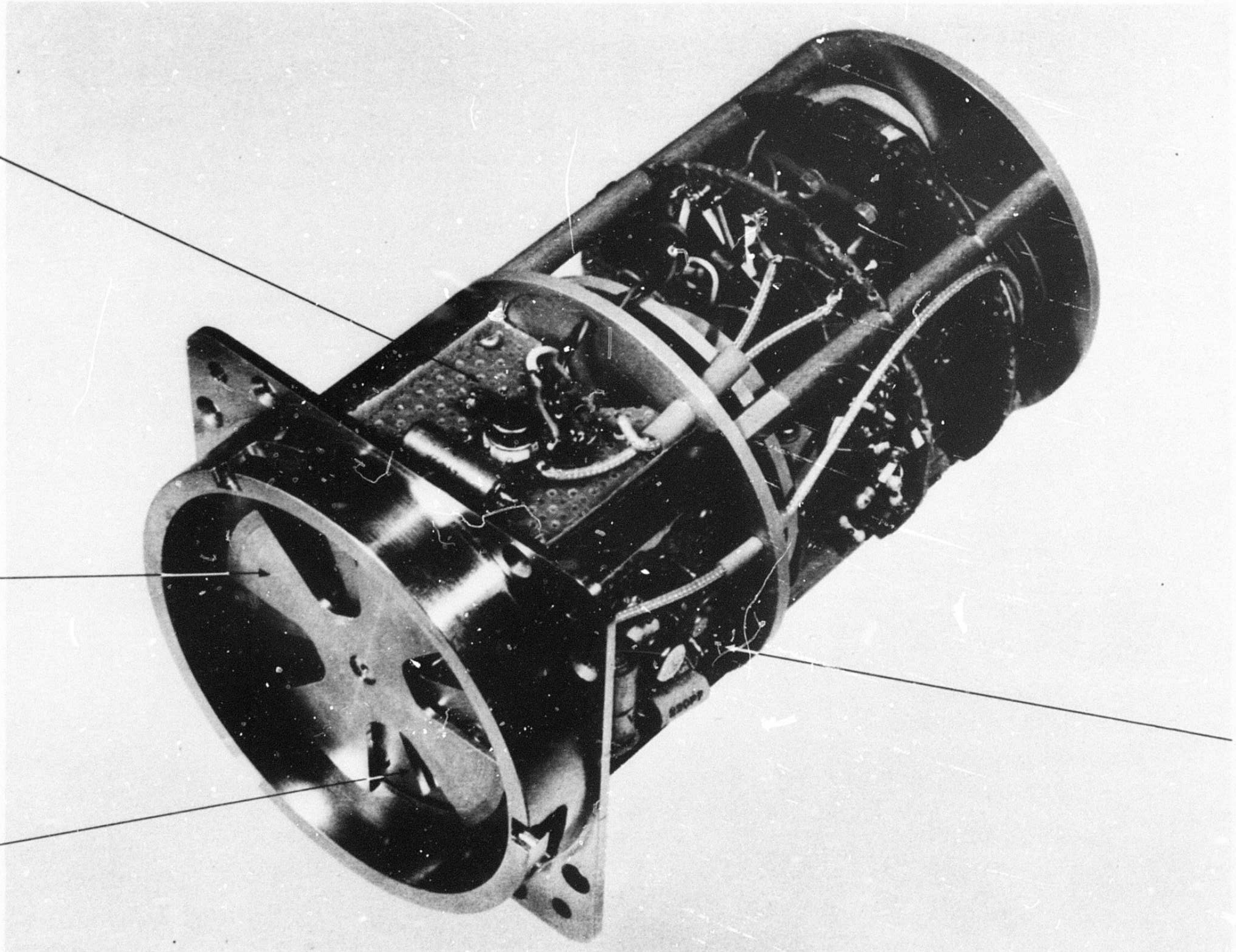

Fig.7. The field mill showing rotor and collector

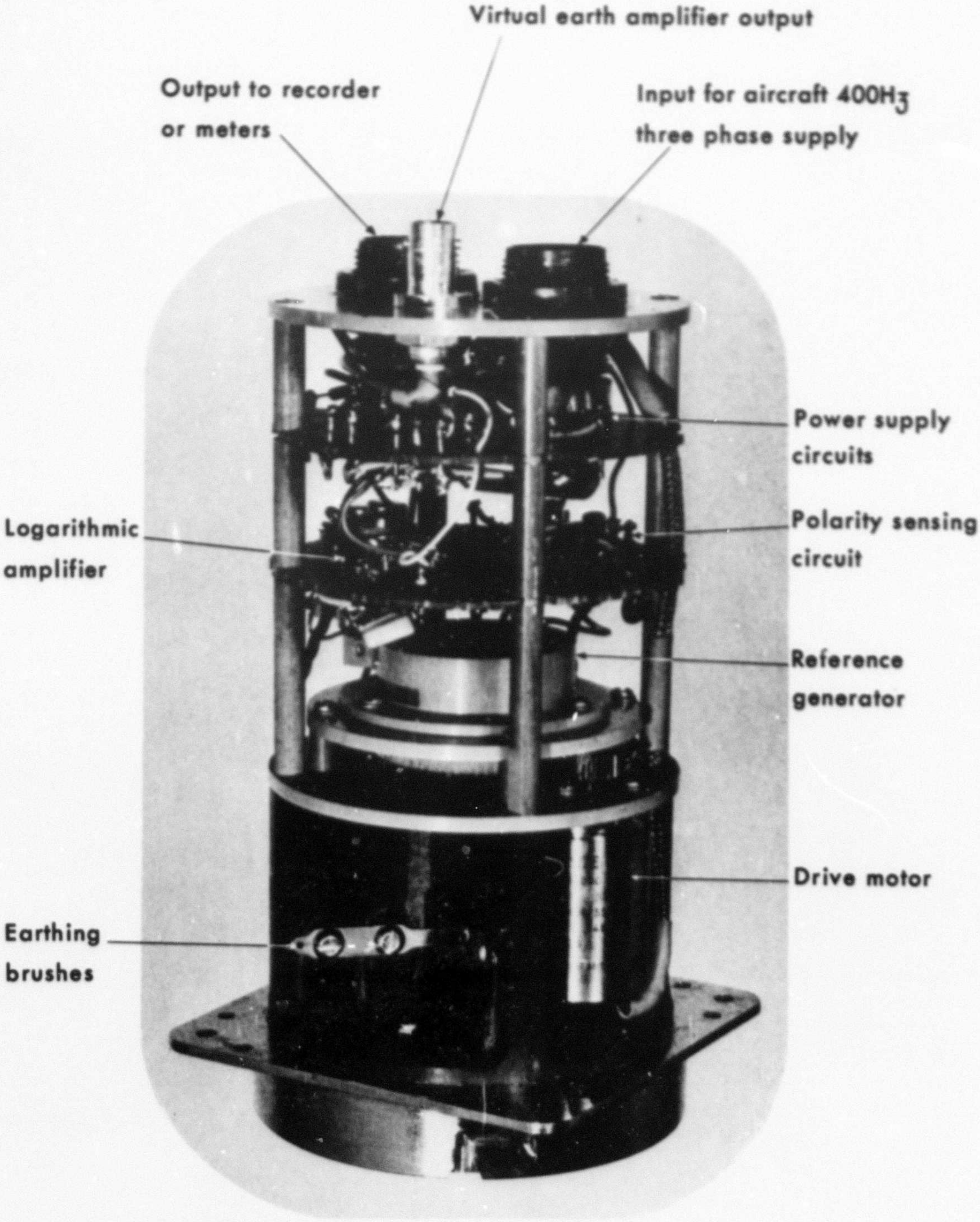

Fig.8. The field mill showing reference generator and drive motor

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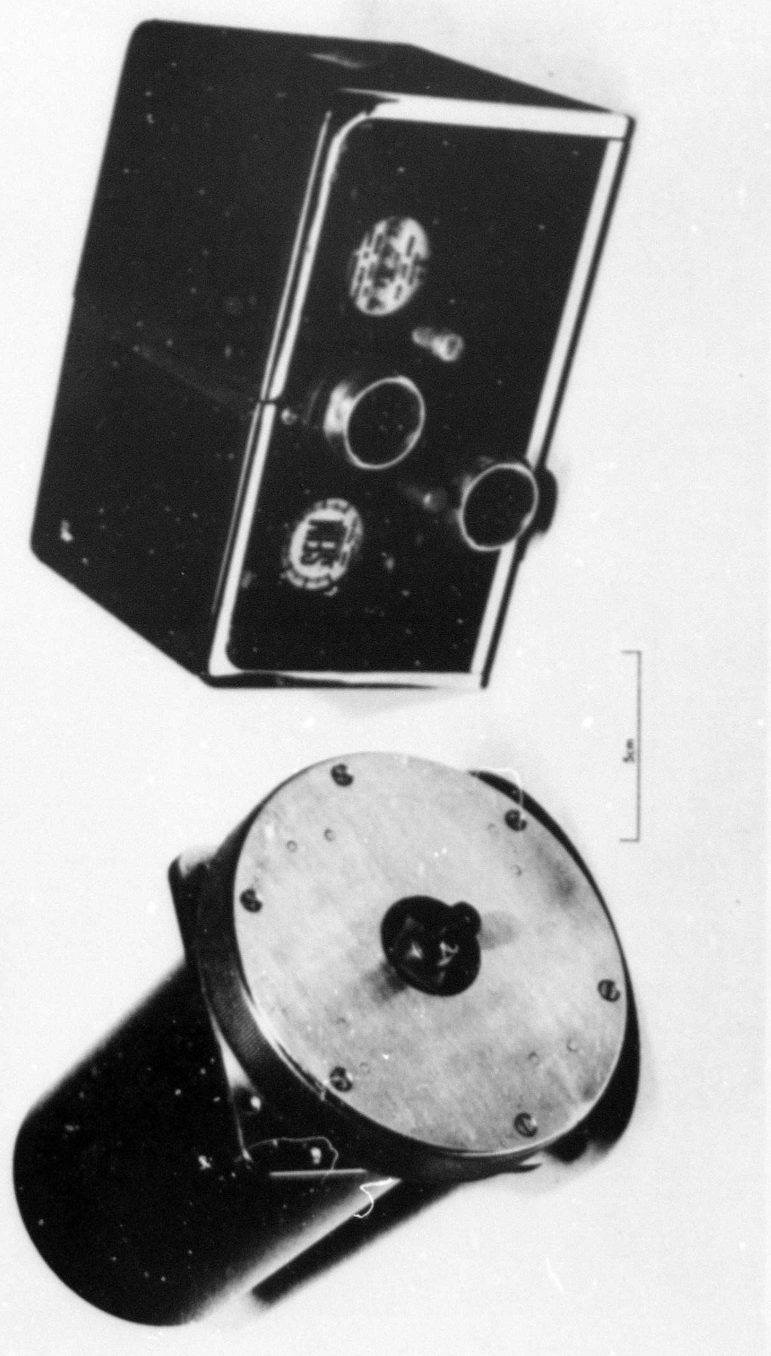

Fig.9. The field mill with calibration cover and a suitable recorder

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Fig. 10

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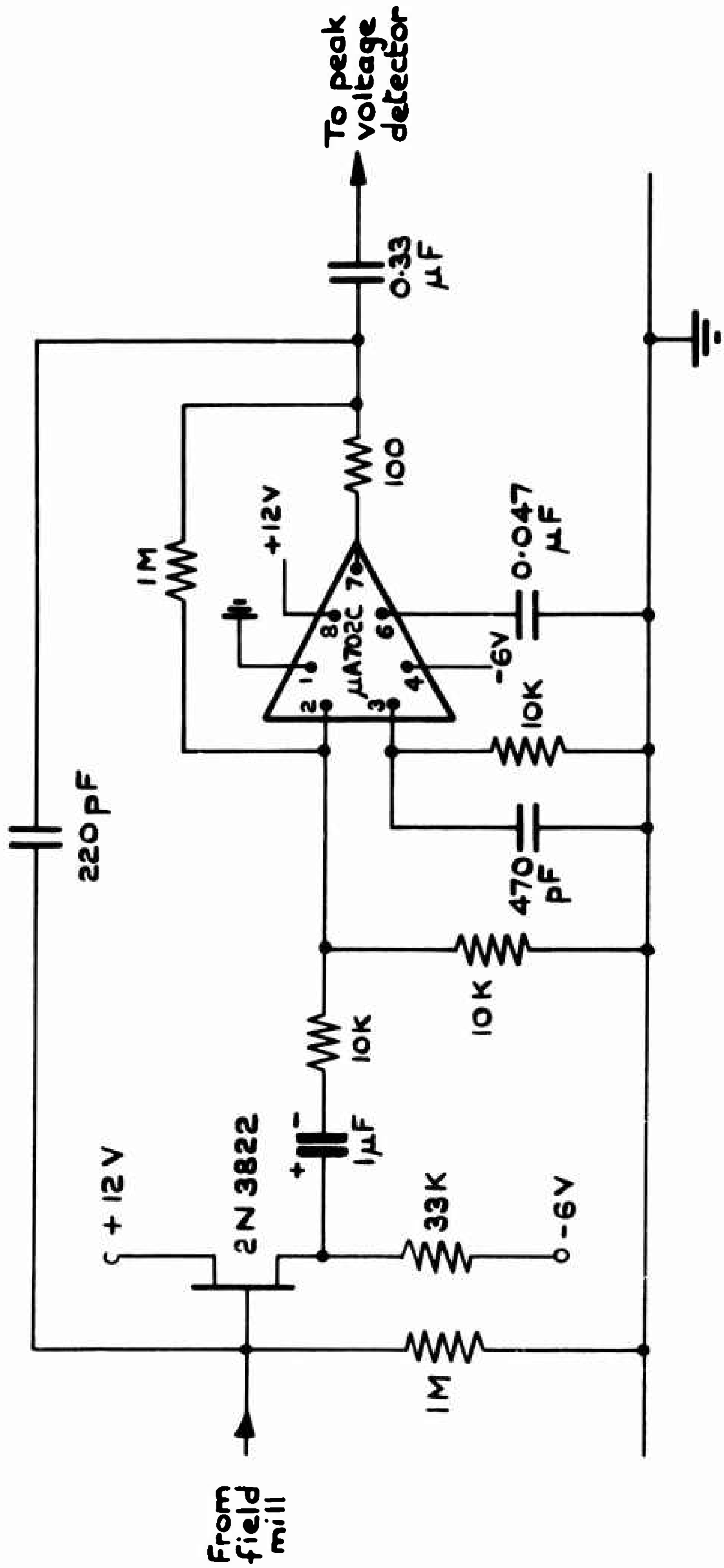

Fig.10 The virtual earth amplifier

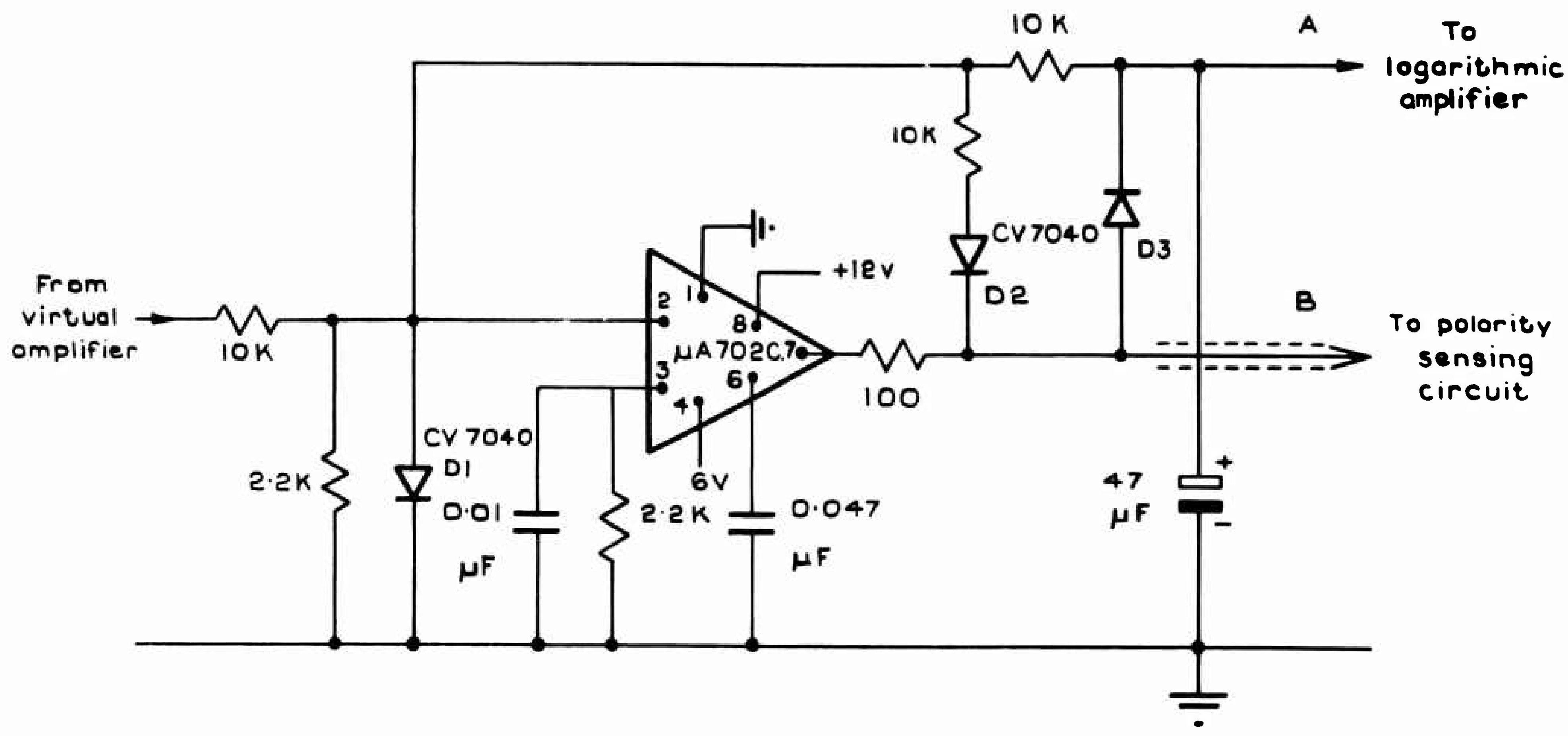

Fig. 11 The peak voltage detector

Fig.12

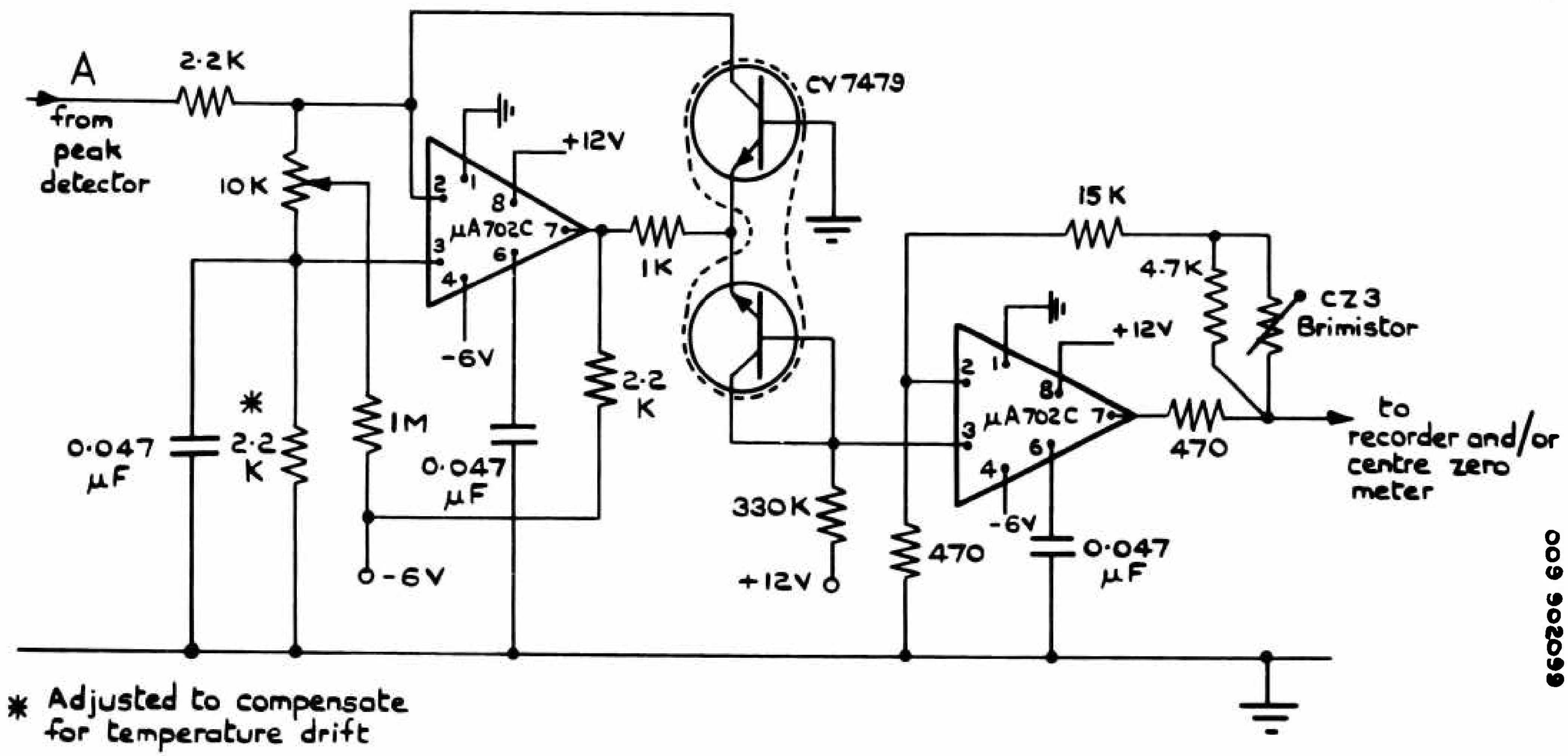

Fig.12 The logarithmic amplifier

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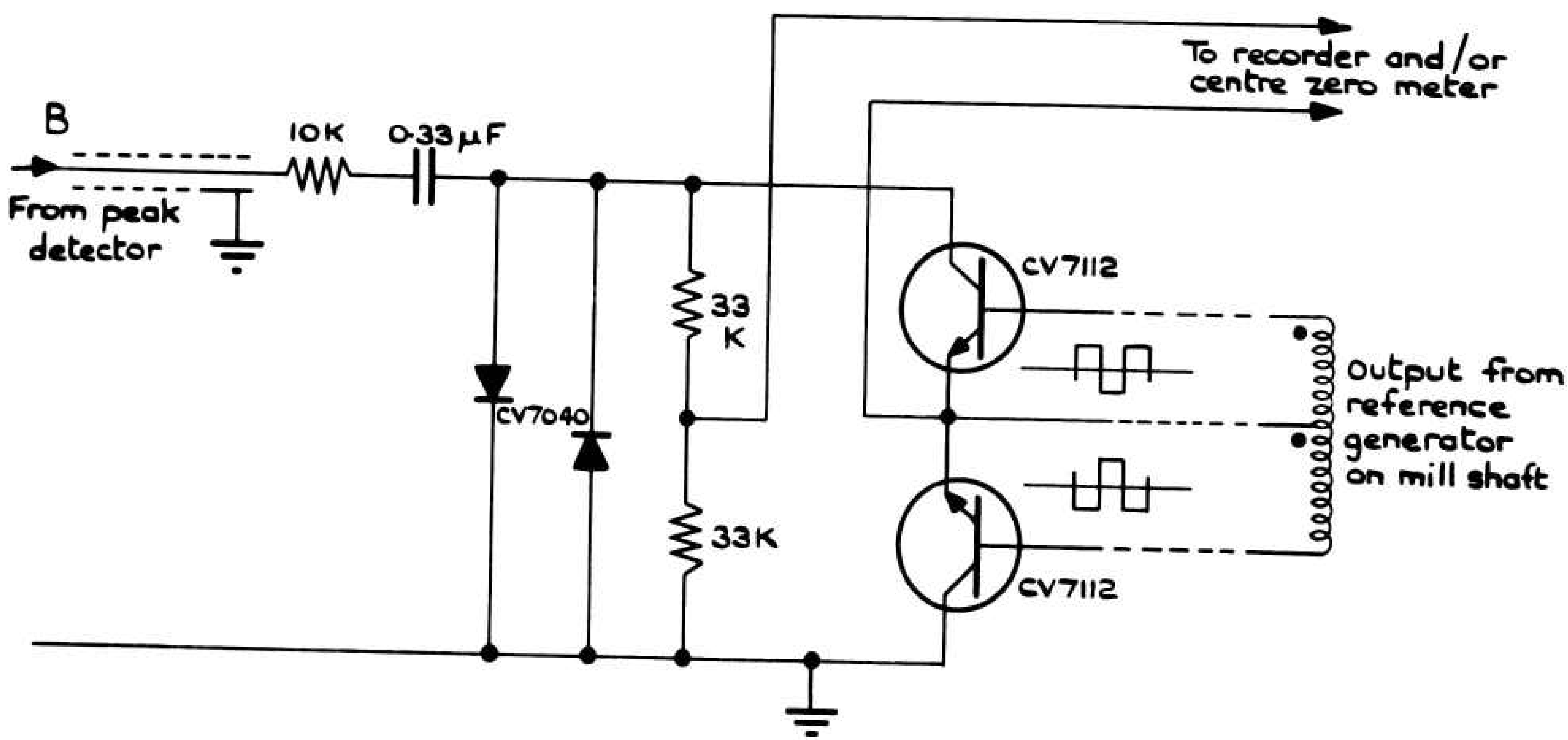

Fig. 13 Polarity sensing circuit

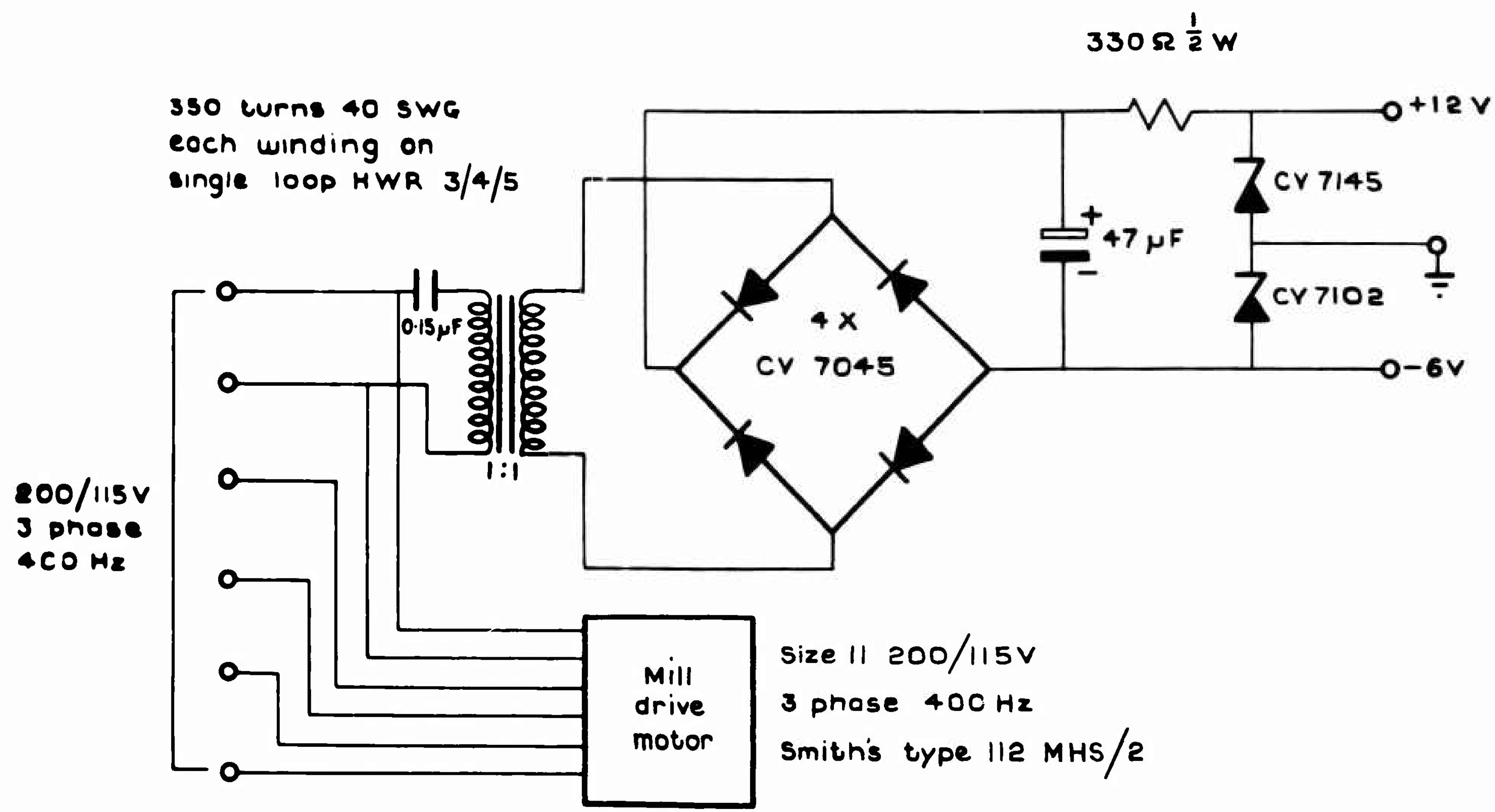

Fig.14 Power supply circuits

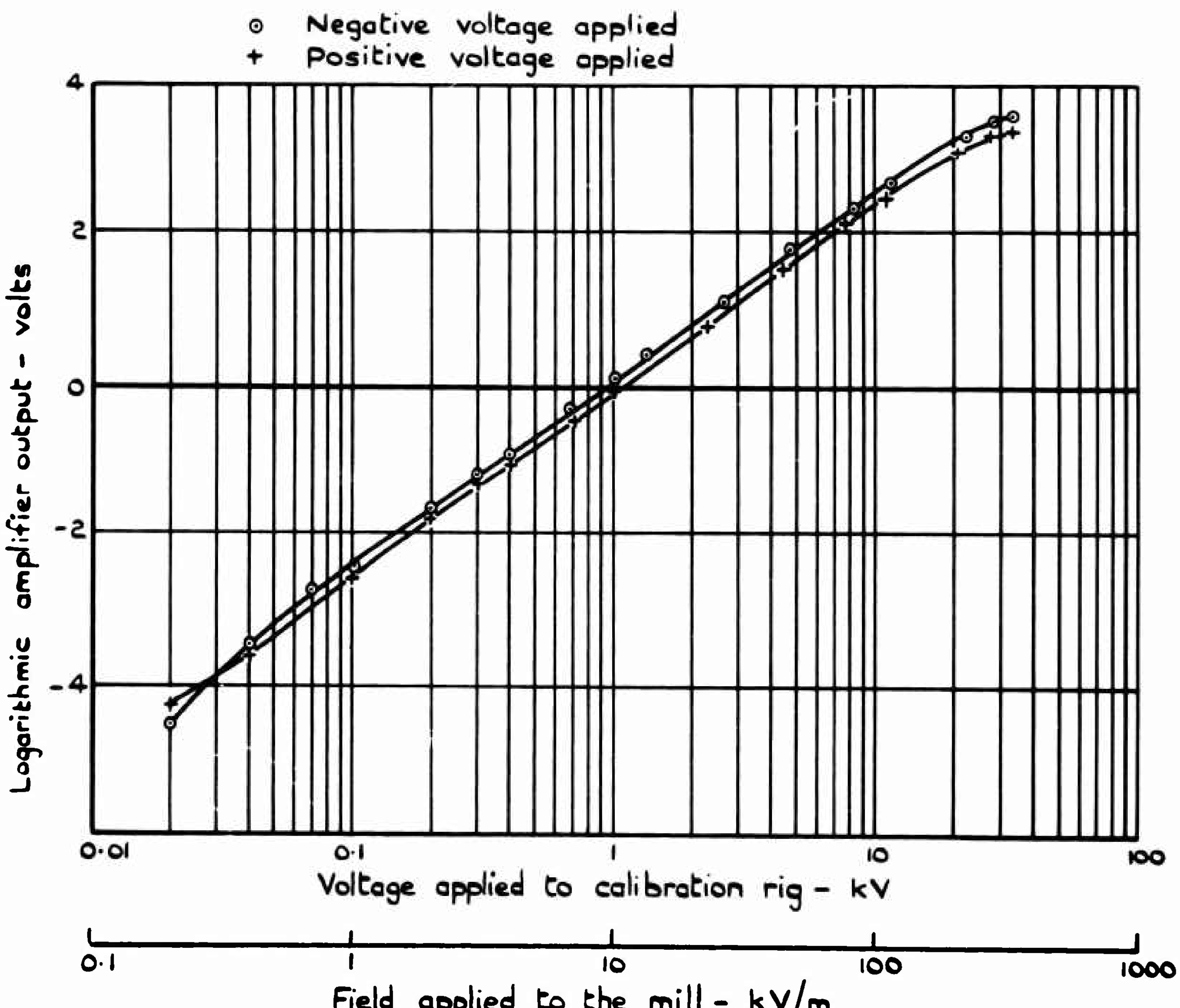

Fig. 15 Relationship between voltage applied to calibration rig, field strength and mill output

Fig.15

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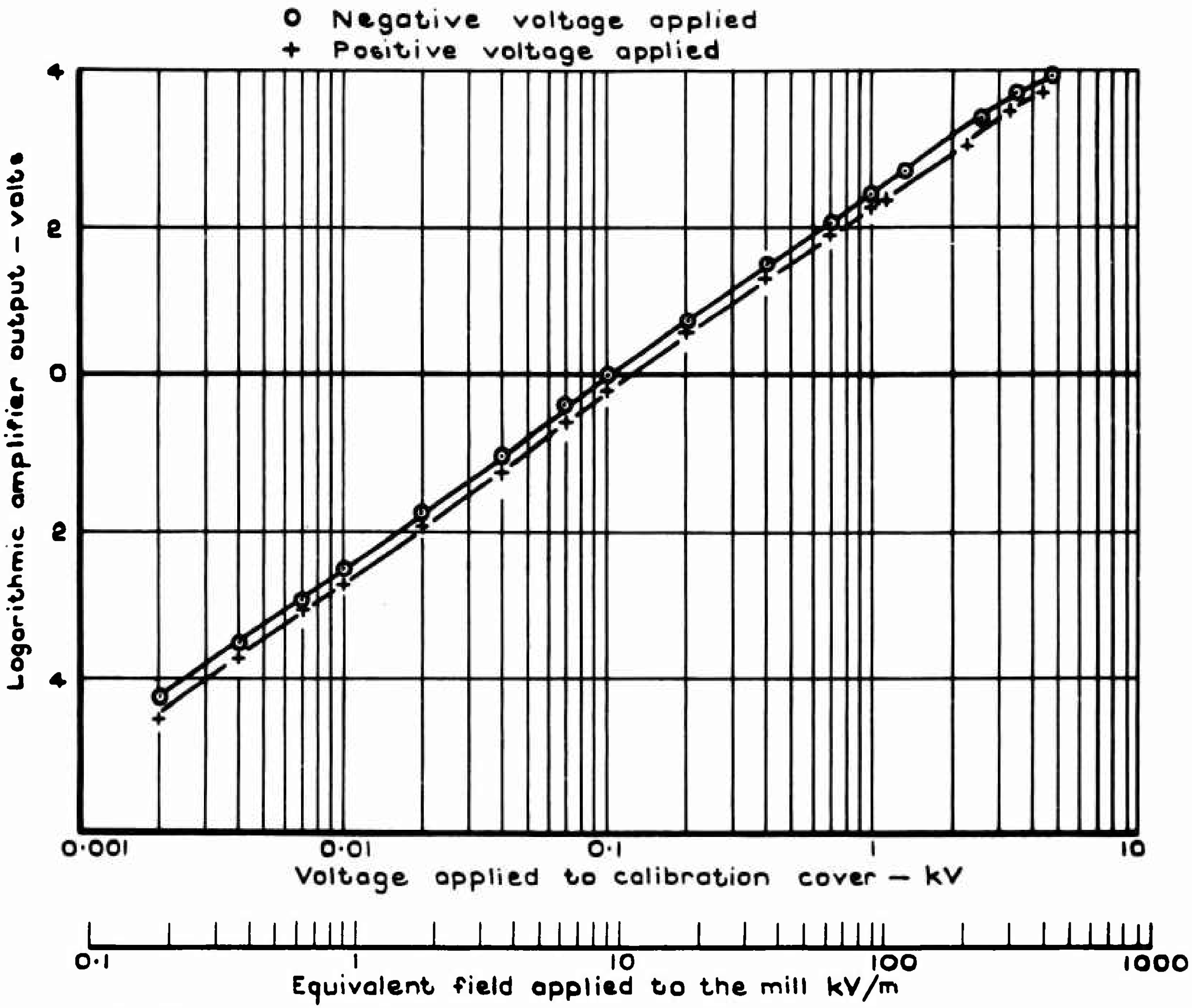
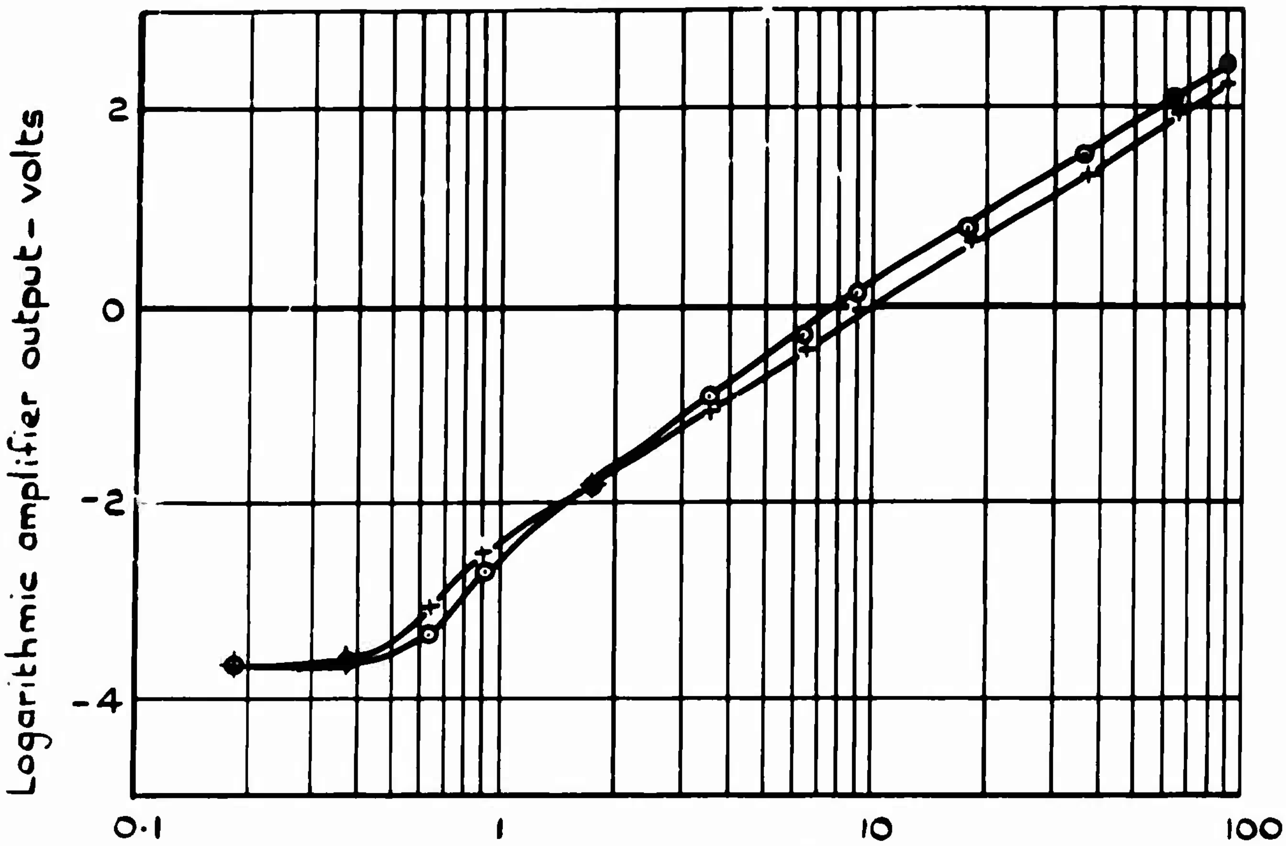
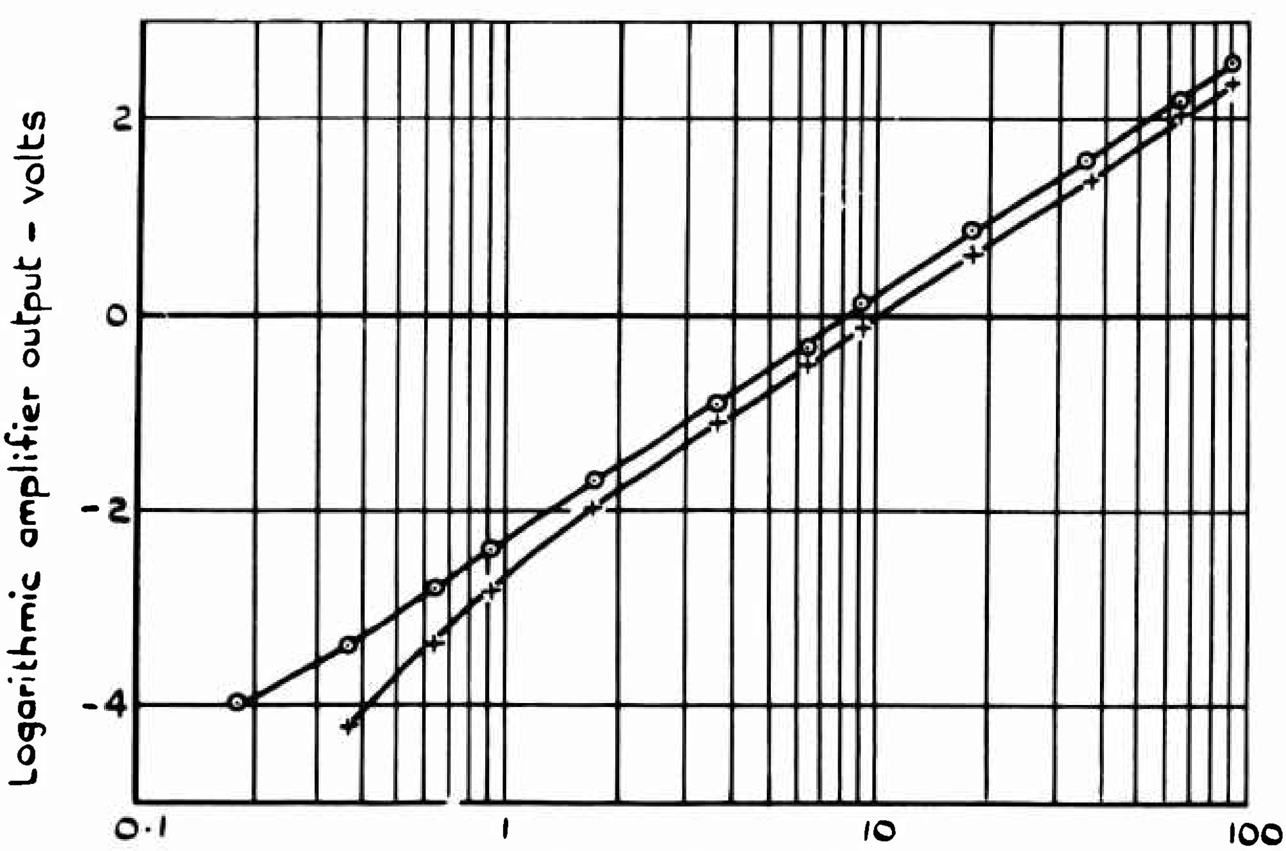


Fig.16 Relationship between voltage applied to calibration cover, field strength and mill output



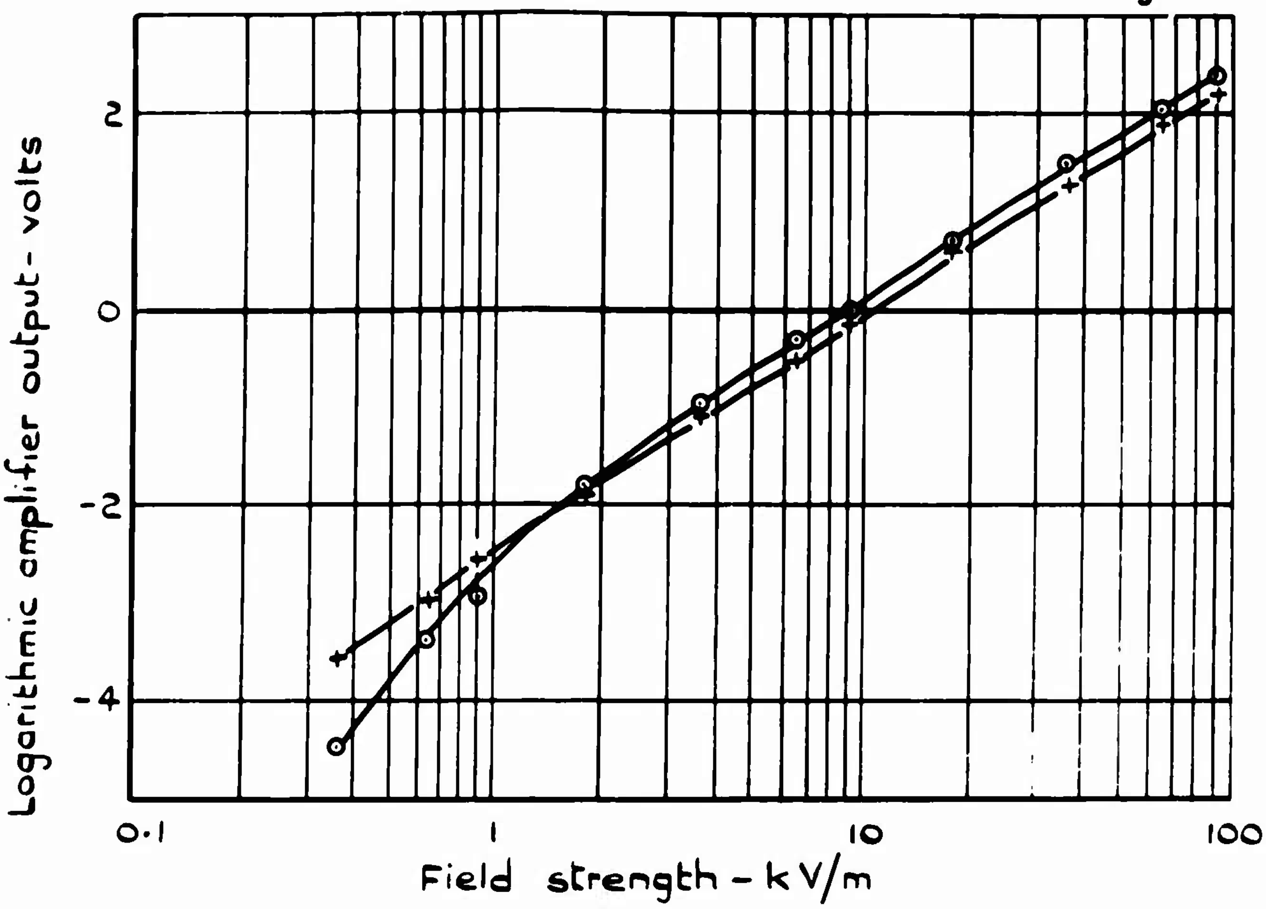
a Response at −16°C



c Rzsponse at 50°C

Fig.17 a–c Calibration of field

Fig. 17 a-c

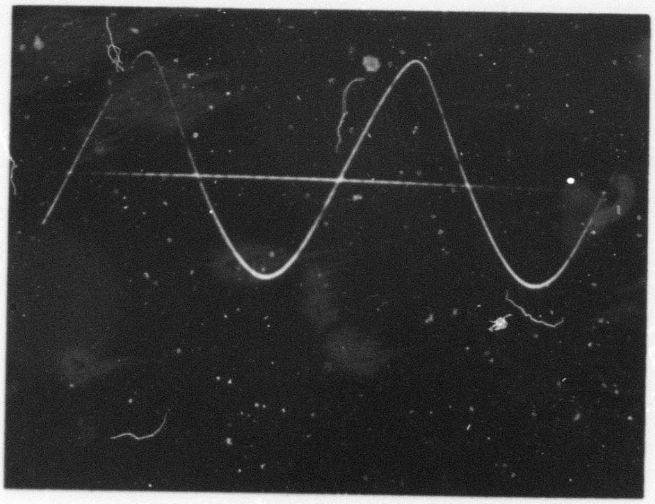


b Response at 22° C

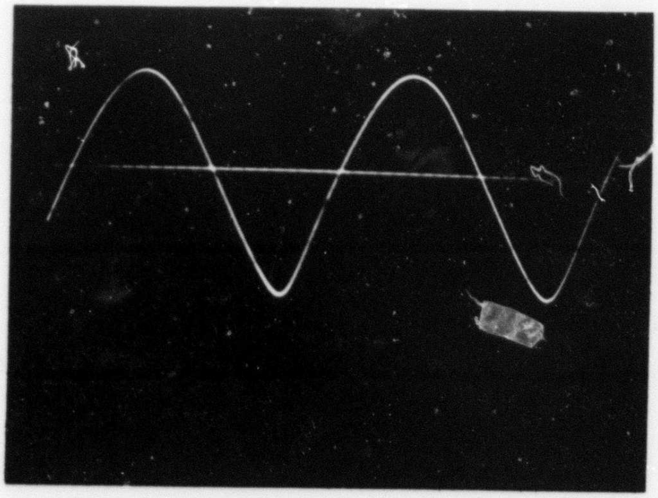
⊙ Negative field
\+ Positive field

f field mill at −16°C, 22°C and 50°C

B



(a). Positive field



(b). Negative field

Fig.18a&b. Waveforms at the virtual earth amplifier output showing the larger negative peak amplitude for negative field

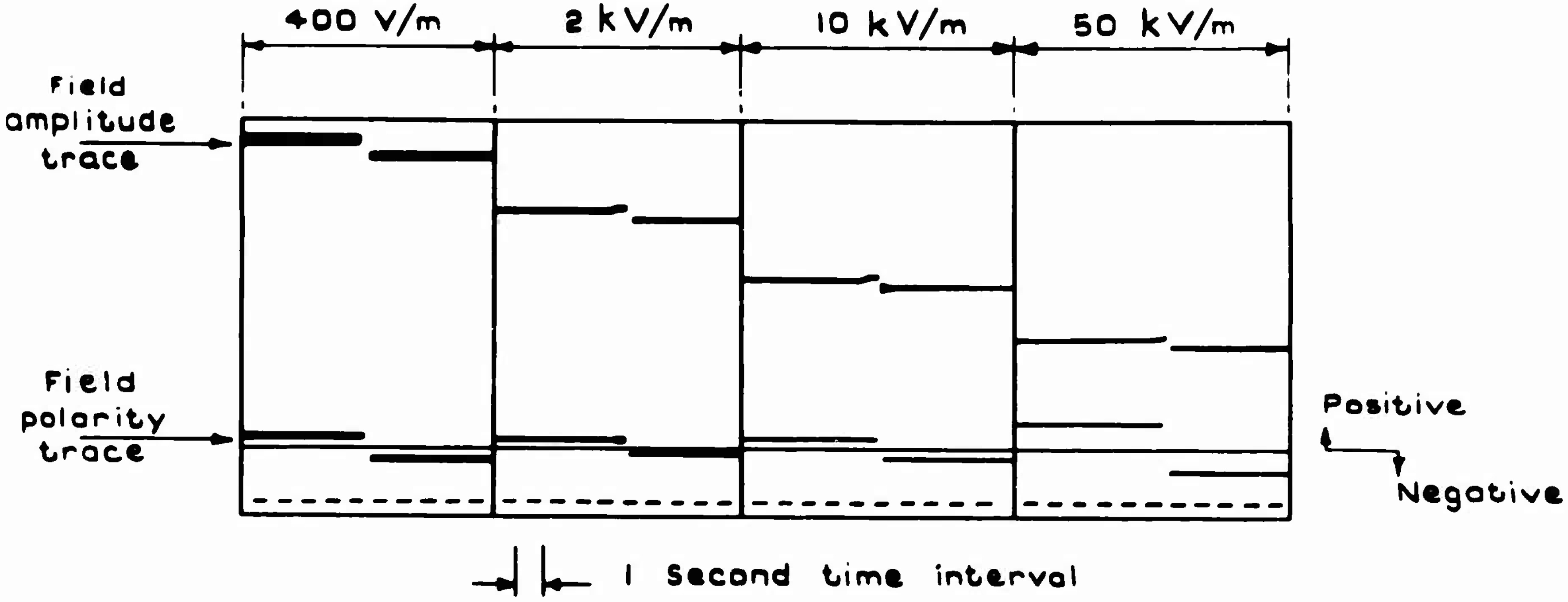


Fig.19 Calibration showing response to rapid field reversals
(Traced from the original record)